

The California Alpine Resort Environmental Cooperative  
presents

# *THE SEDIMENT SOURCE CONTROL HANDBOOK*

PRELIMINARY VERSION — APRIL 2005



WRITTEN BY MICHAEL HOGAN,  
INTEGRATED ENVIRONMENTAL RESTORATION SERVICES  
FOR THE SIERRA BUSINESS COUNCIL



IN COOPERATION WITH  
THE LAHONTAN REGIONAL WATER QUALITY CONTROL BOARD

*“All ethics so far evolved rest upon a single premise: that the individual is a member of a community of interdependent parts. His instincts prompt him to compete for his place in that community, but his ethics prompt him also to cooperate (perhaps in order that there may be a place to compete for). The land ethic simply enlarges the boundaries of the community to include soils, water, plants and animals or collectively: the land.”*

*(Leopold 1949)*

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# ACKNOWLEDGEMENTS

The vision for the California Alpine Resort Environmental Cooperative (CAREC) emerged from ongoing discussions between Michael Hogan of Integrated Environmental Restoration Services, Martin Goldberg of the Lahontan Regional Water Quality Control Board and ski resort personnel. Many tensions over erosion issues between regulatory and ski area managers were due to the lack of good information on how best to control sediment in highly disturbed alpine areas. The idea to work together collaboratively to develop field trials was supported early by Harold Singer of the Lahontan Regional Water Quality Control Board, Amy Horne of the Sierra Business Council and a number of ski areas including Northstar-at Tahoe, Mammoth Mountain, Heavenly Lake Tahoe, and Alpine Meadows. With initial support from the Lahontan Regional Water Quality Control Board, a pilot program was launched to set up field plots and learn from different types of erosion-control treatments.

CAREC emerged from this pilot program as a collaborative partnership that includes representatives from ski resorts, Lahontan Regional Water Quality Control Board, US Forest Service, Tahoe Regional Planning Agency, consulting firms, Integrated Environmental Restoration Services and the Sierra Business Council. Time, resources, and technical input are all provided by the members plus outside 'experts' such as the Natural Resource Conservation Service (NRCS), the Nevada Resource Conservation District, and University of California Davis.



**TEAM**  
ENGINEERING & MANAGEMENT, INC.  
Bishop • Mammoth Lakes

The key people who have worked throughout the pilot phase to help advance this program, install field trials, actively respond to earlier drafts of these pages, and commit to learning together about erosion control processes in disturbed alpine areas include:

Paquita Bath, Vice President, Sierra Business Council

Lou Cayer, Heavenly Ski Resort

George Cella, Lahontan Regional Water Quality Control Board

Todd Ellsworth, Ecologist, Inyo National Forest

Alex Fabbro, Planning Department, Mammoth Mountain Ski Area

Naomi Garcia, Environmental Scientist, TEAM Engineering & Management, Inc.

Martin Goldberg, Environmental Scientist, Lahontan Regional Water Quality Control Board

Melanie Greene, Scientist, Parsons Water and Infrastructure

Larry Heywood, Snow and Ski Safety Consultant

Michael Hogan, President, Integrated Environmental Restoration Services

Amy Horne, Research Director, Sierra Business Council

Eric Knudson, Squaw Valley USA

John Loomis, Director of Operations, Northstar-at-Tahoe

Erin Lutrick, Hydrologist, Inyo National Forest

Clifford Mann, Director of Mountain Maintenance, Mammoth Mountain Ski Area

Cadie Olsen, Trinity Environmental

Michael Schlaffman, Winter Sports Specialist, Inyo National Forest

Randy Westmoreland, Eastside Watershed Program Manager, U.S. Forest Service

Many thanks also to Karyn Erickson of the Sierra Business Council for the layout of this 2005 preliminary version of the Sediment Source Control Handbook.

Finally, developing collaborative programs that directly affect key businesses and water quality, requires a high degree of personal and institutional commitment. We acknowledge the commitment of all the CAREC team members to share their experiences, invest in experiments, and improve our understanding of sediment source control in ski areas throughout the Sierra Nevada.

I am grateful for the opportunity to work with this collaborative and serve as editor for this handbook. We look forward to continued cooperation on behalf of the Sierra Nevada.

A handwritten signature in dark ink, appearing to read 'Paquita Bath' with a stylized flourish at the end.

Paquita Bath  
Vice President  
Sierra Business Council

# INTRODUCTION TO THE SEDIMENT SOURCE CONTROL HANDBOOK

Sediment is a major water pollutant in the Western United States today. Wherever development takes place, disturbed areas are prone to sediment movement. Ski resorts are no exception. Large cut and fill, steep graded ski runs, can pose a serious threat to nearby waterways. Unfortunately, effective methods to control erosion for drastically disturbed alpine areas have not been well researched or documented. Despite a long list of 'BMPs', or recommended 'best management practices', attempts to stabilize disturbed alpine areas continue to produce inconsistent results.

To date, there has been little effort to develop a systematic approach — with specific goals, documented procedures, and ongoing monitoring — to control erosion in ski resorts. Projects are undertaken in a trial and error fashion, sometimes resulting in successful outcomes, and sometimes producing less than optimal results. While there is a broad range of knowledge across resorts, information sharing has been limited.

The California Alpine Resort Environmental Cooperative (CAREC) came together in 2003 to develop a process for planning and implementing erosion control projects and to experiment, through field plots, with various approaches to control sediment on site and thus reduce erosion. The purpose of the partnership is to use field plots to develop on-the-ground practices to better manage erosion and maximize sediment source control on ski area properties. The underlying philosophy is that a collaborative approach between land managers, field practitioners and regulators is the best way to develop an effective, functional and workable set of practices that parties can adapt to fit their needs while greatly enhancing their ability to control sediment in ski areas.

The group meets two to three times a year to share field trial results and challenges. CAREC uses an adaptive management process to plan, implement, and measure erosion control projects and then share information with other practitioners and regulatory personnel. This 2005 Handbook expresses the preliminary approaches and findings of an ongoing program to document cost effective and measurable improvements in sediment source control practices in Sierra ski resorts. The Handbook is made up of three sections:

Part I: Guiding Principles – provides an adaptive management approach to planning and implementing erosion control projects;

Part II: Technical Notes – describes treatment approaches as a starting point for developing better practices, procedures, and monitoring protocols.

Part III: Literature Review – references appropriate information for planners, practitioners, monitoring personnel and scientists involved in upland sediment source control projects.

Thanks to the State Water Resources Control Board, this pilot project will grow to incorporate field trails in at least six different ski resorts and substantial monitoring of sediment source control. An updated version of the Sediment Source Control Handbook, will incorporate monitoring results and CAREC's improved ability to control sediment in 2008.

# SIERRA BUSINESS COUNCIL



The Sierra Business Council (SBC) is the only membership-based regional organization devoted to securing the social, natural, and financial health of the incomparable Sierra Nevada. Founded in 1994, the award-winning SBC achieves its mission through leading-edge research & publications, on-the-ground programs and fee-for-service, and grass roots membership and community networking. Business, government, non-profit, and civic leaders use SBC to meet, share-ideas, gain access to resources and expertise, and put plans into action. Partnering with local communities, and in partnerships such as the California Alpine Resort Environmental Cooperative (CAREC), the Sierra Business Council helps communities plan for and achieve their visions for the future.

SBC is entering its second decade as an award-winning, regional business organization. In response to the enormous challenges facing the region, the Sierra Business Council helps Sierra communities work together to steer the region's economy, environment and communities in directions that ensure long-term prosperity. Recent accomplishments include:

- Being chosen by Governor Arnold Schwarzenegger for his prestigious 2004 Environmental and Economic Leadership Award.
- Developing the bipartisan coalition behind the landmark Sierra Nevada Conservancy bill, signed by the Governor, which invests in our natural, cultural, and historic assets.
- Training business and civic leaders in our world-class Sierra Leadership Seminar to improve individual professional skills while enhancing the civic infrastructure of our region.
- Securing funding for the Town of Truckee to explore development of a railyard brownfield to extend the vibrant downtown;
- Convening hundreds of Sierra business and civic leaders to address critical topics such as affordable housing, fostering creative communities, and the state of the Sierra.
- Publishing award-winning research documents like the *Sierra Nevada Wealth Index*, *Planning for Prosperity*, and *Investing for Prosperity* that are used every day to build sustainable wealth in our region.
- Partnering with the Edward Lowe Foundation to provide our members business and entrepreneurial resources plus a new SBC e-News & On-Line Networking tool.
- Developing a partnership of ranchers and conservationists to maintain ranching as a fundamental part of the Sierra's economy and landscape – conserving over 30,000 acres of working ranchland in the Sierra Valley;

SBC is proud to provide programs, research and documentation, such as the *Sediment Source Control Handbook*, that can stimulate residents and decision makers to work together to ensure that the Sierra Nevada remains one of the most desirable places to live, grow a business, and raise a family. The CAREC partnership will be expanded between 2005 and 2008 to ensure that our knowledge and understanding of sediment source control on steep alpine slopes continues to improve.

*For more information on the Sierra Business Council or to become a member,  
please visit [www.sbcouncil.org](http://www.sbcouncil.org).*



# THE CALIFORNIA ALPINE RESORT ENVIRONMENTAL COOPERATIVE

## SEDIMENT SOURCE CONTROL HANDBOOK PART III

### LITERATURE REVIEW

PRELIMINARY VERSION — APRIL 2005

WRITTEN BY MICHAEL HOGAN,  
INTEGRATED ENVIRONMENTAL RESTORATION SERVICES  
FOR THE SIERRA BUSINESS COUNCIL  
IN COOPERATION WITH  
THE LAHONTAN REGIONAL WATER QUALITY CONTROL BOARD

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### INTRODUCTION TO THE LITERATURE REVIEW

The California Alpine Resort Environmental Cooperative (CAREC) came together in 2003 to develop a process for planning and implementing erosion control projects and to experiment, through field plots, with various approaches to control sediment on site. In addressing an issue as large and complex as erosion control, CAREC wanted to determine what we know, what we don't know and what we need to learn. This is an essential element of the adaptive management cycle discussed in Part I: Guiding Principles. As part of the Sediment Source Control Handbook, CAREC requested a Literature Review that references appropriate information for planners, practitioners, monitoring personnel and scientists involved in upland sediment source control projects.

The ability to return disturbed sites such as ski slopes to a high level of effective soil-plant function requires knowledge and understanding of ecological, physical and operational processes. Too often, this information is not easily available when erosion control projects are planned and implemented. Actual field-level or field-relevant research or other literature tends to be difficult to find or simply non-existent in the case of high alpine areas. Much of the information available is written by manufacturers and suppliers – with their own marketing slant.

This Review attempts to collect as much relevant scientific information on erosion and restoration-related subjects as possible. It is intended to be a working document that will be added to over time as additional research becomes available. Information is cited on erosion control and restoration in the following sections:

- **Section One: Erosion – Key Concepts**  
Establishes a common understanding of what is meant by erosion;
- **Section Two: Variables that Influence Erosion Rates**  
Describes types of erosion and particular variables that affect erosion rates.
- **Section Three: Treatments for Sediment Source Control**  
Suggests issues to consider when applying different types of treatments in support of sediment source control objectives.

The Literature Review complements Parts I & II of the *CAREC Sediment Source Control Handbook (2005)*.

### FRAMING THE ISSUE

#### DEFINITION(S) OF EROSION

The entire process commonly referred to as 'erosion' actually consists of two closely related processes: 1) erosion, or the 'detachment or breaking away of soil particles from a land surface by some erosive agent, most commonly water or wind; and 2) sedimentation or "subsequent transportation of the detached particles to another location" (Flanagan 2002). It is important to understand the nature of these two processes, since addressing them requires quite different techniques and approaches.

Typically, controlling erosion requires keeping soil particles attached to one another and to the soil matrix. Native soils usually do this through the 'aggregation' process (Kay and Angers 2002 -

see pg a-263 section 7.4.3). Soil aggregates are combinations of soil particles that are bound together. Typically this process is the result of physical and biological, especially microbial, processes (Horn and Baumgartl 2002). When soil is disturbed, aggregates tend to disaggregate and are more prone to erosion. Once soil particles begin to move, it is extremely difficult to capture fine silt and clay particles, which are typically responsible for a great deal of water quality pollution and degradation. Thus, the CAREC work and this literature review focuses on 'sediment source control' — keeping soil particles attached and at the same location.

## AN INTRODUCTION TO EROSION

Erosion and sedimentation pose a serious problem throughout the world. Any land 'improvement' or development is almost always associated with the potential for accelerated erosion and associated water pollution. This is especially true in mountainous regions where steep slopes and relatively young and/or poorly developed soils create ideal conditions for accelerated erosion once an area is disturbed. In order to take meaningful action to reduce or control erosion to acceptable levels, and thus protect water quality, it is useful to develop an integrated, comprehensive understanding of what erosion is and what we currently know about controlling it.

Erosion is generally a 'systemic' or functional issue rather than a two-dimensional surface issue æ the product of an entire system of environmental interactions rather than simply the amount of plant cover on a site. When a system is 'healthy' or operating at a high level of functionality, erosion will be low as soil particles will stay connected to each other on site. When one or more components of the system have been disturbed, erosion – the disaggregation of soil particles – coupled with sedimentation – or movement of those particles – is likely to increase.

Background, or 'natural' erosion tends to take place in an equilibrium with other watershed elements such as infiltration, stream flow, stream bank stability, vegetative community and so on. When disturbance takes place, this equilibrium is disrupted, resulting not only in increased sediment movement, but in an increase in surface water flow, an increase in stream water volume and velocity, a decrease in stream bank stability and a decrease in watershed water storage (Selby 1993; Dudley and Stolton 2003). On a watershed basis, accelerated erosion and sedimentation results in removal of watershed 'capital', or the carbon rich soil organic matter that drives so many important processes within a watershed. Carbon provides energy that in turn drives ecosystem processes. Once this 'capital' is diminished, the ecosystem tends to function at a somewhat lower level.

While diminished functionality may be barely noticed at small scales, when large areas such as roads or ski runs are developed, watershed function can be severely disrupted. When this happens, input and output erosion 'variables' are no longer in balance and often result in a downward spiral of ecosystem 'damage' or negative impacts (Daily, Matson, and Vitousek 1997). By replacing components of the larger soil-plant processes such as soil organic matter, seed, mulch, infiltration and so on, erosion can be reduced and water quality can be protected.

Most of the currently accepted 'erosion control' practices, based on models such as the Universal Soil Loss Equation, focus largely on the 'C' or cover factor. Thus, emphasis has been placed on plants or 'revegetation' as the primary solution to erosion control on disturbed sites. However, processes need to be put back as a system rather than as single components. The Literature Review captures the best academic research done to date on treatments that address soil-plant processes to maintain soil particles in place on steep slopes.

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**EROSION OVERVIEW — FROM INTERNATIONAL UNION OF GEOLOGICAL SCIENCES**

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*Erosion, the detachment of particles of soil and superficial sediments and rocks, occurs by hydrological (fluvial) processes of sheet erosion, rilling and gully erosion, and through mass wasting and the action of wind. Erosion, both fluvial and eolian (wind) is generally greatest in arid and semi-arid regions, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates. In uplands, the rate of soil and sediment erosion approaches that of denudation (the lowering of the Earth's surface by erosion processes). In many areas, however, the storage of eroded sediment on hill slopes of lower inclination, in bottomlands, and in lakes and reservoirs, leads to rates of stream sediment transport much lower than the rate of denudation.*

*When runoff occurs, less water enters the ground, thus reducing site productivity. Soil erosion also reduces the levels of the basic plant nutrients needed for crops, trees and other plants, and decreases the diversity and abundance of soil organisms. Stream sediment degrades water supplies for municipal and industrial use, and provides an important transporting medium for a wide range of chemical pollutants that are readily absorbed on sediment surfaces. Increased turbidity of coastal waters due to sediment load may adversely affect organisms such as benthic algae, corals and fish.*

*Significance: Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems. In the USA, soil has recently been eroded at about 17 times the rate at which it forms: about 90% of US cropland is currently losing soil above the sustainable rate. Soil erosion rates in Asia, Africa and South America are estimated to be about twice as high as in the USA. FAO estimates that 140 million ha of high quality soil, mostly in Africa and Asia, will be degraded by 2010, unless better methods of land management are adopted.*

*Human or Natural Cause: Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture (plowing, irrigation, grazing), forestry, construction, surface mining and urbanization. It is estimated that human activities have degraded some 15% (2000 million ha) of the earth's land surface between latitudes 72° N and 57° S. Slightly over half of this is a result of human-induced water erosion and about a third is due to wind erosion (both leading to loss of topsoil), with most of the balance being the result of chemical and physical deterioration.*

## SECTION ONE: EROSION – KEY CONCEPTS

### SECTION OVERVIEW

This section describes several concepts essential to a full understanding of erosion and key terms used throughout the literature and practice of sediment source control. The section also includes general information about the state of erosion control knowledge, the extent of the erosion problem, and prediction capacity.

### DRASTIC DISTURBANCE

‘Drastic disturbance’ defines areas where “...the native vegetation and animal communities have been removed and most of the topsoil is lost, altered, or buried. These drastically disturbed sites will not completely heal themselves within the lifetime of [a person] through normal secondary successional processes (Box 1978).” Drastically disturbed sites describe CAREC treatment areas, such as ski runs, road cuts and fills and building sites. These areas must be considered as functionally and biogeochemically distinct from the pre-disturbance (native) site condition and treatment must focus on restoring structure and function, especially in the soil, if long term or sustainable solutions to erosion are to be implemented (Kay and Angers 2002) (Torbert, Burger 1994 and 2000), (Bradshaw 1992) (Whitford and Elkins 1986). While some sites may be lightly disturbed and may subsequently support vegetation, drastically disturbed sites most often require soil amendments and tilling or loosening.

### SEDIMENT SOURCE CONTROL

The process commonly called ‘erosion’ actually consists of both erosion and sedimentation (See Framing the Issue above). Whether we address erosion or sedimentation will dictate to a great extent, the overall cost and effectiveness of treatment as well. For instance, by focusing on erosion, we attempt to keep soil particles in place, an approach commonly referred to as ‘sediment source control’. Dealing with sedimentation, on the other hand, commonly involves ‘treatment’ of sediment-laden water downstream or downslope from the sediment source.

An innovative program has begun within the Lake Tahoe Basin, where a consortium of entities, led by the California Tahoe Conservancy, have developed what are being termed “Preferred Design Guidelines” (California Tahoe Conservancy 2002). They suggest that in project planning and implementation, the following design criteria be considered in this order of importance:

- 1) Sediment source control;
- 2) Hydrologic design and function; and
- 3) Conveyance and treatment.

This approach assumes that keeping sediment on site and in place, is more effective (both from a cost and environmental standpoint) than attempting to capture and treat it downstream. This approach is the outcome of an understanding that the most cost effective method of reducing sediment is to ensure that it doesn’t move in the first place.

### A DOSE-RESPONSE (AGRONOMIC) VS 'CAPITALIZATION' (WILDLAND) APPROACH

It is useful to differentiate between agricultural and 'ecological' approaches to revegetation, erosion control and restoration. The two main approaches are:

1. Dose-Response - refers to a system in agriculture or landscaping, such as a field of corn or a backyard garden, where a specific amount of fertilizer is applied with a pre-defined output or response. These types of systems are designed for a continual dose (input) and response (output) for as long as the desired process is in place. Generally, this type of system is artificially imposed in an area and is not designed to be self-sustaining.
2. Wildland – refers to a one-time investment or re-capitalization of a disturbed site. The desired outcome of a wildland treatment is typically a no- or low-maintenance, self-sustaining site as continual input and maintenance is not practical or cost-effective. Adequate amounts of materials as well as physical manipulation must 'capitalize' or 'invest' the system with nutrients, organic matter, carbon or other needed elements.

### A FUNCTIONAL APPROACH

The ability to develop and apply effective erosion control techniques and materials depends to a great degree upon understanding of the processes of erosion over time. If an erosion control practice is to be effective, it must directly address one or more of the processes involved in erosion for the long term. For many years, plant cover (revegetation) alone has been used as a measure of erosion control effectiveness. While plant growth can be forced, through the ongoing use of adequate water and nutrients, the literature summarized here strongly suggests that: 1) an erosion resistant landscape is the result of a robust and well-functioning soil-plant system; and 2) the effective control of erosion on disturbed sites depends to a large extent on re-creating and re-integrating ecosystem function.

Cummings (2003) suggests that when assessing restoration or site 'success' we look not primarily at structure (the makeup of the physical plant community) as much as essential functional elements such as nutrient cycling, infiltration (hydrologic function) and energy capture (plant growth/carbon storage) on those sites. This approach is gaining popularity since it is becoming more apparent that while a site may 'look' good, visual interpretation is prone to individual bias and that bias is largely dependent upon levels of training and experience, which varies widely between individuals. Further, simple visual observations cannot discern internal function such as infiltration or nutrient content of the soil and it is these two latter elements that drive so much of the erosion process.

### STATE OF EROSION CONTROL KNOWLEDGE

There has been a great deal of information put forth over many years regarding erosion and its control. Unfortunately, some of this information is inadequate for planning and implementing

erosion control projects. We suggest at least four reasons for this situation, based on Sutherland, 1998a, 1998b and Benoit/Hasty 1994:

1. Single variables: many if not most studies tend to look at one or two variables. Multivariate studies are difficult to implement and interpret. However, restoration in a drastically disturbed site includes a wide range of variables. Therefore, single variable studies may be misleading or difficult to understand in a multivariate environment.
2. Site specificity: studies and tests that are done somewhere else in different climates, soil types and types of disturbance may not be relevant to sites in the Sierra Nevada or the arid west.
3. Inadequate experimental design: a number of erosion control studies have not been adequately designed and therefore the information derived may not be robust or dependable. For instance, Sutherland, in a critical review of rolled erosion control product studies found that very few studies had the scientific rigor to be dependable (Sutherland 1998a and 1998b). An explanation for this lack of rigor, is that many erosion control studies have been conducted by product manufacturers or suppliers. The implementers did not set them up as scientific experiments with statistical accuracy. Further, most of these studies were not presented to peer-reviewed scientific journals, but rather were presented in trade journals.
4. Time: most studies are not tracked over a long enough time period. Even Sutherland has only suggested that studies be more rigorous but does not consider effectiveness over time. Time is a critical consideration when designing and assessing projects, especially where soil restoration is important (Richter and Markewitz 2001; Bloomfield, Handley and Bradshaw 1982).

## EXTENT OF THE PROBLEM

How important or pervasive is erosion? One often hears the comment “But isn’t erosion a natural process?” Several sources were considered in attempting to answer this question. According to Gray and Sotir (1996), annual sediment yields for the US range up to at least 2 billion tons per year. Of the total amount eroded, about 1/4th to 1/3rd reaches the ocean with the rest being deposited in flood plains, river channels, lakes and reservoirs. They report that “siltation and nutrients (nitrogen and phosphorus) from erosion impair more miles of rives and streams than any other pollutant”.

Erosion rates range from a low of 15 tons/mile<sup>2</sup>/year for natural or undisturbed areas to a high of 150,000 tons/mile<sup>2</sup>/year for highway construction sites, or a maximum difference of 10,000 times (US EPA 1973). According to Scheidd (1967), roads may be associated with erosion rates 10-50 times above background. According to Wark and Keller (1963), “Exposure of soil during the construction period can result in sediment production equal to 10 times the rate from cultivated land, 200 times the rate from a grassland, and 2000 times that from forest land”.

The California State Division of Soil Conservation found that roadways in the South Lake Tahoe area were the source of 78% of the total sheet and road erosion. Further, they noted that: "Ski slopes that are established by clearing mountainsides have marred the landscape and created erosion problems at the Heavenly Valley ski area in South Lake Tahoe. Erosion and land scars are noticeable, even though considerable effort has been expended to establish vegetation on the sterile granitic soil" (Resources Agency 1969). Grismer and Hogan, in Tahoe specific research, found erosion rates on disturbed sites to be up to 530 times greater than similar native areas (Grismer and Hogan, in submission).

### PREDICTING EROSION

The ability to predict erosion has been important in designing and justifying many erosion control projects in the past. Erosion prediction is usually based on one or more currently used models. Many of the current models address erosion as primarily a surface phenomena. However, commonly used models such as the Universal Soil Loss Equation (USLE) and other related modes (RUSLE, CREAMS, GLEAMS, WEPP etc.), have proven inadequate to effectively predict erosion in wildland settings. Therefore, these models may be misleading when used to quantify the impact of treatments such as plant cover, mulch treatment and so on.

While models are useful as ways to envision erosive processes, a number of researchers suggest that actual control of erosion is likely to be enhanced by focusing on physical processes in the soil and interactions between components than by focusing on model outputs (Bradshaw 1992; Torri and Borselli 2000; Whitford and Elkins 1986; and Wilkinson, Grunes and Sumner 2000). For instance, Agassi (1996) suggests that "the successful design of soil conservation programs will be more easily achieved by studying the relationship between rainfall characteristics, sealing of the soil surface, and the ensuing decrease of infiltration rate than by studying and modeling erosion processes, as is currently being done." In Section Three we address specific approaches to erosion based on ecological processes rather than model assumptions.

## SECTION TWO: VARIABLES THAT INFLUENCE EROSION RATES

### SECTION OVERVIEW

This section describes the types of erosion and the variables that define whether, and to what extent, erosion occurs on a given site. Each variable affects erosion rates. An excellent description of types of erosion, and erosion processes, is provided by Gray and Sotir (1996) in Biotechnical and Soil Bioengineering Slope Stabilization (pgs 19-30). When more than one variable is impacted in a disturbance event, erosion is likely to increase. Table 1 lists the various types of erosion, what they are caused by and what influences them.

Table 1: Erosional Processes – Their Causes and Influencing Variables

| Process                          | Cause  | Variables   |
|----------------------------------|--|---|
| Splash detachment                | Rain drop impact   | Amount, size of droplets  |
| Sheer detachment                 | Surface flow   | Amount of water   |
| Freeze detachment                | Water expansion upon freezing  | Amount of water in soil, surface cover, air temperature, cloud cover                      |
| Transport                        | Water velocity   | Amount and speed of water   |
| Deposition                       | Slowing of water; filtering of water; exceeding waters capacity to suspend particles | Velocity change, filtration mechanism   |
| Mass failure, rotational failure | Differential soil densities, sliding layer, differential pore pressure               | Different infiltration levels (including oversaturation) of one layer relative to another |

### TYPES OF EROSION

Erosion is generally split into two categories: water and wind. A third type of erosion, which is also related to water is referred to as ‘frozen water’ or ‘winter’ erosion, which includes snow and snowmelt erosion and frozen soil or ‘freeze-thaw’ erosion (McCool 2002). However, additional types of erosion such as colluviation and mass failures are also important.

#### *Water*

Liquid water erosion is the most commonly cited, and possibly best understood, type of erosion. The linkage between this type of erosion and water quality is relatively obvious. Splash detachment, transport, sheet flow, rill and gully concepts are part of water erosion. A great deal of literature describes these processes such as Torri and Borselli (2000), Le Bissonnais and Singer (1993), Moore and Singer (1990), Wischmeier and Smith (1978) and many others.

### *Freeze Thaw*

Soils subject to freeze/thaw conditions have different processes affecting erosion and runoff measurement. Edwards and Burney (1987) used a laboratory rainfall simulator to test three Prince Edward Island agricultural soils (varying in soil texture) for runoff, splash volume, and sediment loss under varying conditions of freeze/thaw, ground cover and potential for erosion.



Figure 1: Freeze-thaw erosion showing detached soil particles

With bare soil, freeze/thaw significantly increased sediment loss by about 90%. Using the same procedures, Edwards and Burney (1989) examined the effects of freeze/thaw frequency, winter rye cover, incorporated cereal residue, and subsoil compaction on runoff volume and sediment loss. Wooden soil boxes were subjected to: 1) simulated rain at the end of a 10-day freezing period, and 2) at the end of the 5th 24-hour freezing period of a 10-day alternating freeze-thaw cycle (freeze-thaw). Where the soil was continuously frozen for 10 days, there was 178% greater sediment loss and 160% greater runoff than with daily freeze/thaw over the same period, but there was no difference in sediment concentration. Incorporated cereal residue decreased sediment loss to 50% and runoff to 77% of that from bare soil, suggesting that mulch can significantly reduce erosion in freeze-thaw conditions.

Winter rye cover decreased sediment loss to 73% of that from bare soil. Simulated soil compaction caused a 45% increase in sediment loss. The loam soil showed 16.5% greater loss of fine sediment fractions  $>0.075\text{mm}$  than the fine sandy loam which showed 23.4% greater loss than the sandy loam.

### *Frozen Water and Wind*

Little research is available regarding the amounts and types of wind or frozen water erosion in the Sierra Nevada or other resort regions, even though the bulk of precipitation falls as snow in these resort regions. However, wind may represent a more insidious (and effective) erosive agent on bare, disturbed areas than water. Evidence indicates that wind erosion is significant and can have devastating effects on soil quality, soil nutrient cycling and long-term soil productivity (Fryrear 2000; Leys 2002; Stetler 2002a). According to Fryrear (2000): "While the transport capacity of the wind is much less than that of water, wind erosion can remove the entire nutrient-rich soil surface regardless of field size or location." In other words, while wind may not move as much sediment as water, the material that is preferentially moved by wind is the lighter soil fraction; i.e. the organic matter and fine soil particles which have a much higher propensity for negative water quality impacts than do the more coarse particles.

Thus, wind erosion can be a highly effective degradation variable that should not be overlooked. Further, wind is less noticeable but possibly more constant than water erosion. Each time a gust of wind affects a bare area, the soil moved can, over time, be significant since it will be ongoing over an entire dry season. A significant body of evidence exists that indicates that wind erosion is significant and can have devastating effects on soil and water quality, soil nutrient cycling and long-term soil productivity (Fryrear 2000; Leys 2002).

### ***Mass Failures***

Mass failure involves a downward and outward movement of soil on a slope. According to Gray and Sotir (1996) "... mass movement [of soil] involves the sliding, toppling, falling, or spreading of fairly large and sometimes relatively intact masses." (pg 20). Mass failure usually occurs along a failure plane, is the result of loss of shear strength and is exacerbated by positive pore pressure within the soil itself.

Mass failures have the potential to do a great deal of damage in a short period of time. Mass failures include rock falls, rotational slides, translational slides, lateral spreads, flows and creep. Mass failures may be controlled, reduced or eliminated by plant roots. For example, a mass failure on January 1, 1997 occurred along Highway 50, crossing the American River and blocking the river. The damage that occurred to beneficial uses along the river has not been financially assessed, but can only be considered major. This mass failure was partly the result of a forest fire on the upland area adjoining the river. Several houses were completely destroyed. Property damage may have exceeded several million dollars. Ecological damage is difficult to estimate.



Figure 2: This photo of the American River shows a mass failure that blocked the river for some period of time. This slide is believed to be the result of lack of vegetation from a previous fire and defoliation efforts and from water associated with a 100 year precipitation event (1997)

### ***Colluviation***

Colluviation is a less well-known type of erosion that can be significant on bare areas. Colluviation is erosion due to gravitational forces. Saprolitic granite soils are especially prone to colluviation, but all bare soils on steep slopes can be affected by gravity erosion. In fact, melt freeze may act as the disturbing element that can make soil particles available for transport by gravity at some later time.

## VARIABLES AFFECTING EROSION IN THE SOIL STRUCTURE

Soil structure is defined as “The combination or arrangement of primary soil particles into secondary particles, units, or peds” (Brady and Weil 1996). Soil structure may be the most important element controlling erosion in upland sites since structure depends upon a great many physical and biological elements and processes (Kay and Angers, 2002).

These interrelated elements include aggregate stability, infiltration, soil strength, pore space, soil density, water holding capacity, soil organic matter, plant growth and microbial ‘activity’. Soil structure is a critical element of a site’s predisposition toward erosion. According to Kay and Angers (2002): “Soil structure has a major influence on the ability of soil to support plant growth, cycle C and nutrients, receive, store and transmit water, and to resist soil erosion and the dispersal of chemicals of anthropogenic origin. Particular attention must be paid to soil structure in managed ecosystems where human activities can cause both short- and long-term changes that may have positive or detrimental impacts on the functions the soil fulfills”. This statement, and the research that supports it, suggest that soil structure is of primary importance to sediment source control. When soil structure is severely disrupted (see ‘drastic disturbance’ above) that structure must be rebuilt if erosion is to be controlled. The following sections discuss some of the components of soil structure.

### *Infiltration*

To the extent that water infiltrates into and through the soil, it does not run off (Radcliffe and Rasmussen 2002). In fact, runoff can be defined as the point at which water input exceeds the soil’s capacity to absorb or infiltrate water (Eagelson 2002). Infiltration is influenced by a number of factors including antecedent soil moisture, soil texture, surface relief, restricting sub-surface layers, organic matter, pore space and soil density (Battany and Grismer 2000; Brady and Weil 1996;



Figure 3: This road cut photo illustrates lack of cover and infiltration capacity and resulting runoff.

Radcliffe and Rasmussen 2002). High infiltration rates generally result in low runoff. Runoff rates and volumes are critical variables in the erosion process. The literature reported here as well as rainfall simulation underway in the Lake Tahoe area suggest that sediment source control projects will generally be successful to the extent that water can infiltrate the soils. A primary goal of erosion control projects is to develop a system of maximum, sustainable infiltration of water into the soil relative to a native and/or adequate reference site. This state of maximum infiltration is usually related to high organic matter, low-density soil and a robust, soil-plant community (Kay and Angers 2002).

Infiltration is heavily influenced by soil density. Each 'native' soil has a density associated with it. Generally, the more dense a given soil, the lower the infiltration rate (Frits, De Vries and Craswell, 2002). When a soil is disturbed by any type of traffic, especially when wet, that soil becomes compacted, which essentially results in a higher density, lower pore space, and a lower infiltration rate. The terms 'compaction' and 'high density' are used interchangeably although they are not always synonymous. A particular soil in its native or undisturbed state exhibits a particular density (also called 'bulk density') usually given in mass (or weight) per volume. A soils bulk density is usually given in g/cm<sup>3</sup>, kg/m<sup>3</sup> or Mg/m<sup>3</sup>. Once a site has been drastically disturbed and/or impacted with heavy equipment, that soil's bulk density increases. This results in a loss of pore space. Lack of pore space results in increased runoff and thus increased erosion (Kay and Angers 2002; Radcliffe and Rasmussen 2002).

A compacted soil is by its nature high density. Subsoil and parent material tend to also be high density by nature. In some cases where reconfiguration of a site results in subsoil being exposed, such as in a road cut or deeply incised ski run, soil density may be so high as to practically preclude infiltration. In all of these cases, some method of decompaction must take place if infiltration is to be increased to levels where plant growth can proceed and where runoff can be lessened.

Plant growth can be severely limited by compaction. For instance, Josiah and Philo (1985), in contrasting physical properties of mined and unmined soils found that the bulk density of native and ungraded soils were both 1.3 mg m<sup>-3</sup> whereas graded, high density spoils were 1.8 mg m<sup>-3</sup>. Four years after planting, Black Walnut (*Juglans nigra* L.) trees were 35% taller and stem diameter was 31% greater in the ungraded vs the graded and compacted site. Torbert and Burger (1990) compared the survival rate of six commercially important tree species on soil of two different densities. The soil that had been left uncompacted demonstrated a 70% survival rate compared to the 42% survival rate for the compacted soil. For some species, height was almost doubled on the uncompacted site. An extensive treatment of the impacts of compaction to forest and other impacted sites can be found in Forest Land Reclamation (Torbert and Berger, 2000), a chapter in a highly useful book Reclamation of Drastically Disturbed Land, edited by Barnhiesel, Darmody and Daniels, 2000.

### *Depth to restricting layer*

According to Torbert and Burger (2000): "Depth to a restrictive layer is an especially important physical property controlling productivity of trees [and by inference, other plants as well]. In a study to evaluate the effect of various mine soil physical and chemical properties...the most important mine soil property was rooting depth". While rooting depth is seldom considered in most erosion control projects, field experience and numerous measurements of unvegetated sites clearly suggests that shallow rooting depth is often associated with lack of vegetative cover.

Two considerations connecting rooting depth and erosion are:

- 1) Plants need a certain quantity of available nutrients and water. Water especially, is associated with the volume of pore space in a soil. A restricting layer tends to limit the amount of pore space in a soil, thus limiting water availability; and

- 2) When water reaches a restricting layer, the infiltration rate is slowed, thus tending to saturate the soil. Two things can then occur. First, more water will flow over the surface as runoff and second, positive pore pressure in the soil and the different soil densities can lead to mass movements, such as landslides.

## *Nutrient Cycling/Soil Organic Matter*

Soil organic matter has been linked to both establishment and persistence of plant communities in the Lake Tahoe basin and elsewhere (Claassen and Hogan 2002; Baldock and Nelson 2002; Reeder and Sabey 1987; and Bradshaw 1997) as well as an increase in the soils ability to resist erosion. Torri and Borselli (2000) have found that “increasing organic matter content makes aggregates more resistant to sealing and consequently decreases runoff and erosion.” And further “... those relationships indicate that soils with good granular structure (high Fe oxide and organic matter content) are less erodible. (pg G-189)”. McBride (1994) summarizes the functions of organic matter as follows: “In partnership with the clay fraction, organic matter has an extremely important influence on the chemical and physical properties of soils. Critical and beneficial functions of organic matter include:

1. Maintenance of good pore structure accompanied by improved water retention
2. Retention of nutrients (e.g.  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^{+}$ ,  $\text{NH}_4^{+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Cu}^{2+}$ ) by cation exchange
3. Release of nitrogen, phosphorus, sulfur, and trace elements by mineralization, the microbial process by which organic compounds are decomposed and carbon dioxide is released.
4. Absorption of potentially toxic organics (pesticides, industrial wastes, etc.).

## *Aggregates*

According to Cambardella (2002), “A soil aggregate is formed when closely packed sand, silt, clay and organic particles adhere more strongly to each other than to surrounding particles. The arrangement of these aggregates and the pore space between them is referred to as soil structure. Soil aggregates are held together by three classes of binding agents: 1) humic material; 2) polysaccharides (organic sugars); and 3) temporary elements (roots, root hairs and fungal hyphae) (Tisdale and Oades 1982). Soil aggregate formation has been shown to be dependent upon soil organic matter content (Baldock and Nelson 2002; Blackmer 2000; Wilkinson, Grunes, and Sumner 2000). Aggregates in the soil are closely linked to the ability of a site to resist erosion (Kay and Angers 2002).

Soil aggregate formation has been shown to link to soil organic matter content (Baldock and Nelson 2002; Blackmer 2000; Wilkinson, Grunes and Sumner 2000; Kay and Angers 2002) as well as an increase in the soils ability to resist erosion as well as increased microbial populations whose production of extracellular polysaccharides enhances soil structure. These data suggest that organic matter plays a number of very specific roles in reducing erosion and is of critical importance for encouraging aggregates.

## *Surface Cover/Mulch*

Soil surface cover plays a critical role in not only erosion reduction but in other ecosystem processes as well. According to Pritchett and Fischer (1987): “Plant and litter cover is the greatest deterrent

to surface erosion. The tremendous amounts of kinetic energy expended by falling rain are mostly absorbed by vegetation and litter in undisturbed forests. Disturbances caused by logging and other activities reduce infiltration rates and increase surface runoff and erosion” (pg 304).

Surface cover provides the following services:

- Reduces raindrop force (splash detachment);
- Reduces surface flow velocities (sheer detachment of soil particles by both wind and water);
- Reduces evaporation (water loss reduction);
- Reduces radiation influx and efflux;
- Increases soil nutrients (some mulches) (Woods and Schuman 1986);
- Increases seed germination at some levels (Molinar, Galt and Holechek 2001);
- Protects soil from sealing and pore clogging (Singer and Blackard 1978).

Grismer and Hogan (in prep) show that mulches alone could reduce soil erosion from bare slopes by an order of magnitude. However, the type, age and fiber length of the mulch material is important.

## *Plants*

Plants play an important role in erosion processes. Plants are closely linked to the elimination or reduction of erosion and have commonly been employed as the chief line of defense against surface erosion. Gray and Sotir (1996) describe the various services provided by plants including surface protection, surface and subsurface reinforcement of the soil and influence on subsurface hydrology. They describe differences between woody and non-woody plants as well as provide limited sheer strength values for some plants. The role of plants cannot be understated. Since these roles are so complex, we refer to Gray and Sotir as well as other references where these roles are discussed in detail. Plants provide an ‘indirect’ service by providing surface protective mulch. Torri and Boreselli (2000) state, “...the most effective action (of plants) is due to dead leaves and branches laying on the soil surface (mulch).” This mulch, as well as senescent plant roots, play a major role in establishing and maintaining the soil nutrient cycle (Baldock and Nelson, 2002; Pritchett and Fisher 1987; Paul and Clark 1989). Plant roots are a host to soil microorganisms and provide some of those organisms with a source of energy and nutrients (McBride 1994; Paul and Clark 1989; Reeder and Sabey 1987; Smith, Redente and Hooper 1987).

While plants do play a number of essential roles in stabilizing soil and reducing erosion, plants alone do not always limit erosion to acceptable levels (Elliot 2002; Zhang 2002). Grismer and Hogan in recent rainfall simulation experiments on a range of cover types and amounts throughout the Tahoe region, found that plant cover did not always correlate with sedimentation rates and in fact, found that some sites with extremely high cover levels produced an extremely high erosion rate, similar to adjacent bare plots (Hogan 2004).

### *Soil Microbial Communities/Mycorrhizae*

Microbial ‘activity’ is the chief driving force behind most soil function (McBride 1994; Paul and Clark 1989; Reeder and Sabey 1987; Huang and Schnizer 1986; and Whitford and Elkins 1986). Microbial populations are closely linked to and dependent on soil organic matter and soil quality. Microbes contribute to nutrient cycling and availability, aggregate formation, erosion resistance, water-holding capacity, disease resistance and so on. There are a number of microbial ‘types’ that coexist in the soil. A great deal is known about soil microbes and an even greater amount remains to be discovered. Soil microbes are grouped into broad categories of bacteria, actinomycetes and fungi. Soil microbial communities are known to convert most nutrients from an organic form into a plant available form (Blackmer 2000; Killham 1994; Paul and Clark 1989; Tisdale and Oades 1982; Tisdale et. al 1993; Buxton and Caruccio 1979) In some cases, specific fungi are known to enhance uptake of both nutrients and water (Killham 1994 and Allen 1991). These fungi are categorized as Mycorrhizal.

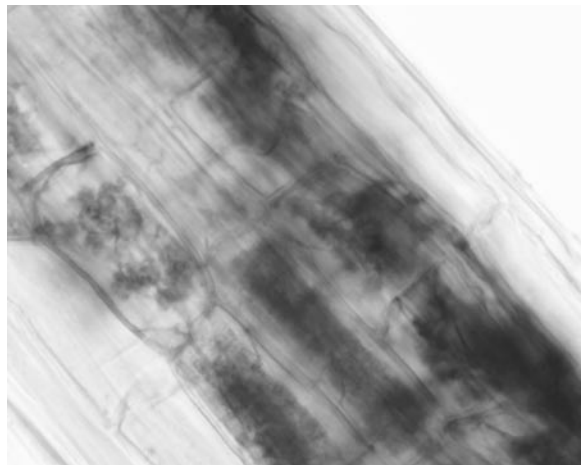


Figure 4: This scanning electron micrograph image shows mycorrhizal colonization in a plant root (photo courtesy of Dr. Vic Claassen, UC Davis).

Mycorrhizae, which means ‘fungus roots’ are an important element of the soil ecosystem. Mycorrhizae have received a great deal of attention with respect to their function and potential for use in disturbed site revegetation (Allen 1992). Mycorrhizae are a specific type of fungi that form a symbiotic relationship with plants. They are one part of an incredibly complex ecosystem of soil microbes.

### *Surface Roughness*

Surface roughness is often overlooked as a significant variable in erosion (Torri and Boreselli, 2000; Batanny and Grismer, 2000). Surface roughness helps determine the velocity at which overland flow can occur, thus influencing both flow velocities and infiltration. Further, surface roughness is often associated with soil clods or aggregates and thus suggests soil stability, at least in an undisturbed and/or stable soil.

### *Soil Surface Sealing/Pore Clogging*

Surface sealing and pore clogging are two potentially related processes. When infiltration of water occurs, fine clays, silts, organic matter and other elements can contribute to the clogging of pores. This process is especially related to splash detachment of fine sediments and subsequent redistribution. In some cases, these fine sediments are redistributed across the soil surface and subsequently dry into a hydrophobic layer called a soil crust. In other cases, this material makes its way into the soil and fills soil pores. In either case, the result is loss of infiltration and subsequent increase in overland flow and related erosion (Moody 2002). Over time, pore clogging and surface sealing may reduce infiltration to a level similar to highly compacted soil. This is an insidious issue in ‘settling ponds’.

## SECTION THREE: TREATMENTS FOR SEDIMENT SOURCE CONTROL

### SECTION OVERVIEW

This section describes various ‘functional’ tools that can be used to develop a sustainable, robust erosion control program. The term ‘functional’ refers to the various functions that exist in an ecological system. Many planners attempt to establish grasses and other plants on a highly disturbed site much as one would plant a lawn or pasture. However, recent research has clearly indicated that vegetation alone may not always be adequate to control erosion (Grismer & Hogan 2004; and in press). To create a self-sustaining soil-vegetation community, this section addresses the restoration of actual functions that have been disturbed or destroyed during disturbance.

A great many erosion control projects are designed and implemented with the project proponent assuming that specific BMPs (Best Management Practices) have been tested and ‘proven’, or that information gathered in various publications or conferences will actually perform as indicated. Unfortunately, that is not usually the case. This section provides tools used in site-specific erosion control and restoration implementation plans.

### DEFINING SUCCESS AS IMPROVING FUNCTIONS

All erosion control treatments define success either implicitly or explicitly. How we define success will determine how we approach a project. For instance, if we envision a successful erosion control project outcome as primarily a well-vegetated area, then we are likely to focus on ‘revegetation’ as our primary treatment. We will seed, fertilize, possibly mulch and irrigate in order to establish that vegetation. Erosion itself may actually take on a secondary level of importance. As an example, some erosion control projects have actually produced erosion (sheet erosion or rills) as an outcome of irrigation, used in an attempt to establish vegetation on treated areas. Some of these sites have been considered ‘successful’ because grass had been established (Hogan, personal observations, summer 2003, 2004, at 5 Sierra ski resorts).

If we define success in terms of function, rather than form (how a site looks), it is likely that we will be much more accurate in assessing ‘success’. In other words, we will be able to determine how a project is working rather than simply how it looks. According to Cummings (2003), the ability to restore function within the soil-plant ecosystem is likely to be the most powerful approach we can take to control sediment at its source. Cummings suggests that restoration of function within a disturbed system should be a primary goal. The usefulness of this concept can be seen in some projects where surface treatments are aimed at plant growth as a primary objective. Recent research on ski runs and highway road cuts has shown that, while it is possible to actually force plants to grow, these plant-dominated projects do not automatically equate with greater erosion control since runoff can still be quite high (Grismer 2004).

According to Cummings and others, the main functions of concern are:

- 1) Hydrologic function (infiltration, storage, transfer of water into and through the soil);
- 2) Nutrient cycling (cycling of nutrients within and through the soil); and

- 3) Energy capture (processing, storage and transfer of energy from the sun as well as capture and transfer of water energy within and through the watershed).

For example, if water infiltrates into the soil, it will move through the watershed more slowly, thus resulting in a lower runoff rate as well as lower volume and velocity of water in the streams. This attenuation of energy will lower overall erosive forces. Without restoring soil hydrologic function, including infiltration, the goals of erosion control are not likely to be met, even though a site may support plant growth (at least as long as fertilizer and irrigation are applied).

Energy capture may be described in two contexts: 1) energy captured and stored in the biota or living things such as plants and soil flora and fauna; and 2) energy stored as water within the soil. Energy capture describes the plant community as well as links to the hydrologic function within a project area. Beyond simply describing plants as a 'form', this approach recognizes the plants function within the ecosystem: they store and then transfer energy to the soil and to animals as food.

This approach also discusses the energy function of the water within an ecosystem as well. For instance, a storm and/or runoff hydrograph represents an energy distribution graph. A hydrograph with a large peak early in the runoff cycle has a much higher probability of erosion than a lower peak later in the runoff cycle. This is also known as peak flow attenuation. A high peak hydrograph describes a much more erosive runoff force than a low peak hydrograph. Water that is stored in the soil as energy is available for plant growth throughout the growing season.

We therefore focus on three main functions: hydrologic function, nutrient cycling and energy capture, for planning and implementing treatments. By maximizing these three functions, soil will tend to remain in place and water within the watershed will tend toward a more natural or background behavior.

## THREE COMMON TREATMENT INDEXES

While most sediment source control efforts focus on liquid water erosion, many of the same processes used to control liquid water erosion are also effective for wind and frozen water-caused erosion (McCool 2002; Fryrear 2000; Tibke 2002). According to Reichert and Elemar (2002) "Water erosion is caused basically by raindrop impact and runoff of excess water, thus erosion and sedimentation control strategies must be based on covering the soil against raindrop impact, increasing water infiltration to reduce runoff generation and increasing surface roughness to reduce overland flow velocity."

The same techniques that are used to protect the soil surface against raindrop impact, namely mulch and live plants, are also effective for protection against wind erosion (by deflecting wind from the soil surface) and for protection against frozen water erosion (by insulating soil against freeze thaw and by providing additionally surface roughness for snow melt). Traditionally, live plant cover has been considered of primary importance in erosion control. However, a great deal of research has shown that total ground cover, and especially mulch, provides the most critical short-term impact or protection (Zhang 2002; Elliot 2002; Grismer and Hogan, in press).

There are an extremely large numbers of attributes that actually define a site's ability to control erosion, such as the extent of the microbial community, particle size distribution, plant type, and

so forth. However, the three most accessible attributes that we often choose to serve as indices or site indexes for erosion resistance, given that they increase sediment control in areas with water and wind pressures are:

- 1) cover (plant and mulch);
- 2) soil organic matter and associated nutrients; and
- 3) levels of infiltration.

## SOIL NUTRIENT TREATMENT ISSUES

Nutrients are critical for both plant and microbial growth in the soil. There are a broad range of both macro (N,P,K), secondary (Ca, Mg, S) and micro (Zn, Fe, Mn, Cu, B, Mb, Mo, Cl, Ni) nutrients. Typically, in the Sierra Nevada and other western mountain ranges (in non-mined sites) macro and micro nutrients tend to be adequate on disturbed sites, except N. However, it is difficult to generalize about adequacy of most nutrients in disturbed wildland settings. Therefore, the ability to gather soil nutrient data from surrounding 'reference' sites will usually be an important step in understanding what is required in a native or self-sustaining system.

Nitrogen (N) is clearly recognized as the most important or generally most limiting nutrient involved in plant growth on disturbed sites (Marrs and Bradshaw 1993; Palmer 1990; Reeder and Sabey 1987; Bradshaw et al. 1982; Bloomfield, Handley, and Bradshaw 1982; Wilkinson, Grunes, and Sumner 2000; Palmer 1990; Bloomfield, Handley, and Bradshaw 1982; Cummings 2003). N is used in the greatest quantities by plants and can be very mobile in mineral form.

While N is known to be limiting, caution should be exercised when determining which material may be needed to replace N or other nutrients. Many water bodies, such as Lake Tahoe, are known to be P (phosphorus) limited. If a fertilizer or amendment contains relatively high levels of P and the soil contains adequate P, additions may result in loss of P from the soil into nearby waterways – a water body pollutant. Therefore, knowledge of both existing soil nutrient conditions as well as release characteristics of the fertilizer or soil amendment itself is important for effective use that minimizes runoff-pollution prevention.

N can be a limitation in both agricultural and wildland ecosystems. An important difference between these two types of ecosystems is that agricultural systems ('dose-response') are designed to receive an input (fertilizer), and produce a response (plant growth) that is then removed from the system. The following season, the same cycle is repeated. Wildland systems, on the other hand, are self-sustaining. That is, they cycle most of their nutrients internally. In a pine forest, for instance, pine needles fall to the ground, are broken down by microbial activity and eventually turn into nutrients for both plants, microbes and macrobes. Therefore, when planning and implementing an erosion control project, an understanding of the soil nutrient content (load) is critical. In preparing project plans, it is important to understand three things:

- 1) What amount of nutrients are in the project site soil?
- 2) What amount of nutrients should be in the soil (measuring a reference site and/or using data from similar sites)? and

## 3) What amount and what type of nutrients need to be added to assure a self-sustaining system?

Several studies suggest that a certain level of nutrients, especially N, must be present in the soil before an adequate plant cover can be established and maintained (Claassen and Hogan 2002; Bradshaw 1997; Li and Daniels 1994; Reeder and Sabey 1987; Bradshaw and Chadwick 1980). Research on disturbed sites in the Lake Tahoe Basin, California and Nevada, showed a correlation between certain nutrient pools, especially nitrogen, and plant cover on previously disturbed sites (Claassen and Hogan 1998). Therefore, knowing current conditions before planning will allow the planner to specify the appropriate amount (and type) of nutrient additions.

Bradshaw et al (1982) discussed the development of N cycling on mined land. They suggested that a pool of at least 1000 kg/ha-1 must be accumulated, after which N cycling by mineralization, plant uptake and litter fall will support a self-sustaining ecosystem. This value compares well with that suggested by Claassen and Hogan (Claassen and Hogan 2002) who found that well vegetated, previously disturbed sites in the Lake Tahoe Basin, were related to a pool of at least 1250 kg/ha-1 total N.

While N is understood as a critical limiting nutrient in most terrestrial semi-arid ecosystems, and N is largely derived from organic matter in those ecosystems, the capacity for the total N contained in that organic matter to mineralize is not consistent or well understood (Baldock and Nelson 2002; Blackmer 2000). Reestablishment of nutrient cycles on disturbed sites is seen as a primary cornerstone in the successful re-creation of a sustainable terrestrial ecosystem capable of reducing erosion, improving water quality, enhancing wildlife habitat and improving other beneficial uses (Haering, Daniels, and Feagley 2000; Macyk 2000; Marrs and Bradshaw 1993; Palmer 1990; Reeder and Sabey 1987; Dancer, Handley, and Bradshaw 1977; Cummings 2003; Bradshaw et al. 1982; Bloomfield, Handley, and Bradshaw 1982; Dodge 1976). Woodmansee et al. (1978) reported that N deficiency can affect the long-term stability of a site by limiting plant growth, thereby increasing erosion from that site.

## ORGANIC MATTER TREATMENT ISSUES

Soil organic matter drives a number of processes in the soil, as discussed in previous sections. Powers (1990) suggested that a decline in forest productivity is linked directly to losses of soil organic matter. It thus may be one of the most important elements of soil function. Noyd et al.(1996) reported that compost had a primary impact on reestablishment of both plant communities and mycorrhizal fungi colonization on taconite mine spoils in the Mesabi Iron Range in Minnesota while arbuscular mycorrhizae (AM) inoculation played a secondary role. Johnson (1998) suggested that manipulating edaphic factors through additions of soil organic matter may be more cost effective on low P sites than large scale mycorrhizal inoculation. These edaphic factors include adequate organic matter in the soil and many of the connected elements, as mentioned above.

The inclusion of organic material in a depauperate (low nutrient) soil may provide additional benefits beyond nutrient additions, such as increased water holding-capacity, increased microbial activity (enhanced cycling of pre-existing nutrients) increased infiltration rates, and a higher cation exchange capacity (Brady and Weil 1996). Soil organic matter has been linked to both establishment

and persistence of plant communities in the Lake Tahoe basin and elsewhere (Claassen and Hogan 1998); (Baldock and Nelson 2002; Bradshaw 1997; Woodmansee, Reeder, and Berg 1978;) as well as an increase in the soils ability to resist erosion. There are a number of types of organic matter including compost, wood chips, manure and others. Each has its own strengths and weaknesses and should be considered carefully before use, especially for amounts and release rates of nitrogen and phosphorus.

## FERTILIZER TREATMENT ISSUES

The use of fertilizer for erosion control projects has been a standard practice for many years. Essentially, fertilizer is used to make up for inadequate amounts of nutrients in the soil (Soil Improvement Committee 1998). Much of the information and the approach to fertilizer use comes from agricultural research. Much less research has been done on wildland system restoration. However, some work has been done by Bradshaw and others in mine reclamation to focus on rebuilding and re-capitalizing the nitrogen cycle in 'derelict' or drastically disturbed sites. These researchers generally found that adequate N cycling was directly linked to organic matter in the soil (Roberts R. D. et al 1980; Bradshaw, Marrs et. al 1982; Bloomfield, Handley et. al 1982; Marrs & Bradshaw 1982; Woodmansee, Reeder et al. 1978). Further, Classen & Hogan (2002) found that adequate organic matter and mineralization of the N in organic matter was directly linked to plant growth. While some of this research has been available since 1980, few findings have been incorporated into ski area work.

Bradshaw and others suggest that rebuilding of the nitrogen cycle is the underpinning of most reclamation or restoration on drastically disturbed land. Reeder & Sabey (1987) and many others support the importance of this approach. Their findings clearly suggest that fertilizers alone are unlikely to rebuild these soil-plant systems to adequate levels of N in a reasonable time unless a very careful application regime is instituted. Yearly applications may increase nutrients to the point of self-sustainability, as Ray Brown was able to show on a mine site in Idaho. However, 25 years were required to do so. In this project, cost was not evaluated but estimates of labor alone could be as high as \$25,000 (Brown and Johnson 1978).

When using fertilizers, it is essential to understand their strengths and limitations and not expect fertilizers alone to completely regenerate self-sustaining nutrient cycling (Tisdale et al 1993). Fertilizers will be seen as part of an overall package of treatment. It is also critical to understand what type and how much fertilizer is actually needed in any particular situation so that under or over application does not become a problem (Tisdale et al. 1993; Soil Improvement Committee 1998).

Fertilizers come in many forms and nutrient amounts. The two most common fertilizers are the 'mineral' and the organically based fertilizers. Further, some mineral fertilizers are coated so that the nutrients are released more slowly. Specific information on fertilizers can be found (Tisdale et. al 1993; Soil Improvement Committee 1998).

## MYCORRHIZAE TREATMENT ISSUES

Mycorrhizal fungi play an important role in most ecosystems. Mycorrhizal fungi are a group of fungi that have the ability to form a relationship with certain plants in an apparently mutualistic relationship. Mycorrhizae can be considered as an important subset of soil microbial components.

A broad range of information about mycorrhizal physiology, morphology, classification etc can be found in Walling, Davies and Hasholt 1993; Paul and Clark 1989; and Killham 1994.

In terms of the benefits of mycorrhizae, there is little doubt that these types of fungi play a critical role in many types of plant growth. Paul and Clark and Killham discuss the myriad of benefits associated with the range of mycorrhizal fungi. The two types of mycorrhizae that are of chief concern in wildland systems, especially relative to restoration, are the vesicular-arbuscular subgroup of the endotrophic mycorrhizae and the ectotrophic mycorrhizae, which form relationships with temperate trees and shrubs (Paul and Clark 1989). Endotrophic mycorrhizae are found on about 90% of the worlds' plants (Israelsen 1980) and so are of critical concern.

The microbial community within a soil are known to drive conversion of most nutrients from an organic form into a plant available form (Paul and Clark 1989; Killham 1994; Tisdale et al. 1993; Buxton and Caruccio 1979; Killham 1994; Tisdale et al. 1993; Buxton and Caruccio 1979). In some cases, specific fungi are known to enhance uptake of both nutrients and water (Killham 1994). A great deal of attention is currently being placed on mycorrhizal fungi and specifically, use of commercial, non-native or non-indigenous inoculum. Noyd (Noyd et al. 1997) and others reported that compost had a primary impact on reestablishment of both plant communities and mycorrhizal fungi colonization on taconite mine spoils in the Mesabi Iron Range in Minnesota while arbuscular mycorrhizae (AM) inoculation played a secondary role.

Johnson (1998) in studying plant response to mycorrhizal inoculation across a phosphorus gradient reported that inoculation with arbuscular mycorrhizal (AM) fungi reduced growth at high soil P levels. This finding is relevant to Tahoe and Sierra Nevada soils that tend to be high in P (Rogers 1974), suggesting that AM inoculation may not play an important role and may, in fact, reduce plant growth on some revegetation sites. This finding is further supported by an unpublished study of a variety of treatments (Longenecker, Senior thesis) on Tahoe granitic soil, including inoculation with non-native (cultured) mycorrhizae. Measurement of growth rates in a sixty day experiment showed that soil inoculated solely with mycorrhizae resulted in a growth rate lower than the control, while soil with compost and organic fertilizer, resulted in growth rates over twice as high as either the control or the inoculated pots.

Further, Johnson (1998) suggested that manipulating edaphic factors through additions of soil organic matter may be more cost effective on low P sites than large scale inoculation. In support of this approach, Sylvia (1990) reported that, after initial infection by vesicular arbuscular mycorrhizae (VAM) on plants used in a mine reclamation site in White Springs, Florida, there was no plant effect at 18 months and that VAM inoculation had no effect on transplant survival. These soils were low in nutrients, thus supporting the nutrient addition findings of Noyd, Pfleger and Norland (1996), Johnson and others.

In another study Noyd et al (1997) reports that adequate rates of compost added to taconite mine tailings produced biomass equivalent to or surpassing a native tallgrass prairie in three years. At the same time, organic matter accrual increased and litter breakdown rate decreased, inferring long-term plant community sustainability. In a greenhouse study, Stahl et al (1998) discuss the capacity of VAM-inoculated Big Sagebrush to better withstand drought than non-inoculated plants. However,

the substrate used was collected from an undisturbed, nutrient-adequate site, further supporting the adequate nutrient concept. Weinbaum and Allan (1996) in a reciprocal transplant study between San Diego and Reno, showed that non-local mycorrhizal inoculum always declined at the exotic site and with exotic hosts, arguing for both locally-collected inoculum and local plant source.

## PLANT TREATMENT ISSUES

Plants play an extremely important role in practically all ecosystems. Plants are linked to and supported by the soil resource/ soil community. For many years, researchers and erosion control writers and practitioners have emphasized the plant or vegetative component of erosion control in revegetation and restoration projects (California Tahoe Conservancy 1987; U.S. Department of Agriculture 1982; Nakao 1976; Leiser et al. 1974). Plants play a great many roles in restoration and erosion control, especially on disturbed sites. Plants are closely linked to the elimination or reduction of erosion and have commonly been employed as the chief line of defense against surface erosion. However, while plants play an essential role in stabilizing soil and reducing raindrop impact, they do not always limit erosion to acceptable levels. (Elliot 2002; Zhang 2002). We suggest that by linking the plant and soil elements, a more effective outcome will be produced.

A healthy, robust soil will be a critical issue for planting of any kind. Drastically disturbed soil will have very different attributes from a slightly or non-disturbed site. Reestablishment of a sustainable plant community on severely disturbed upland sites in the Sierra Nevada has proven difficult (Erman and Others 1997; Leiser et al. 1974).

Aside from surface stabilization, plants also contribute to subsurface stabilization. An increase in root biomass typically results in an increase in physical soil stabilization due to sheer and tensile strength (Gray and Sotir 1996). This fact is useful in ski areas to counter some county or other 'engineering' agencies that may require ski runs to be compacted in order to provide soil strength. However, when soil is compacted, infiltration is decreased and plant roots cannot penetrate easily, thus reducing plant growth to minimal levels see ('Infiltration, Soil Density' section, above). Further, plants have been used successfully in the Lake Tahoe and Truckee areas to successfully hold loose soils of up to 1:1 slopes (Cave Rock Report, in preparation).

One additional consideration for plant use is that claims made by suppliers, may not live up their billing, given that site conditions vary widely.

## MULCH TREATMENT ISSUES

A great deal of information exists regarding the effectiveness of mulch to control erosion. Agassi (1996) states "Mulching is a very efficient means to dissipate raindrop impact and to control the ensuing soil surface sealing, runoff and erosion. Mulching can also reduce evaporation of rainwater and overhead irrigation water. Therefore, mulching can be a vital factor in improving water use efficiency". Mulch provides a number of 'services'. These services are listed in the following Table 2:

Table 2: Mulch Services

| Service                 | Description   | Notes   |
|-------------------------|---|---|
| Surface protection-rain | Protects soil surface from raindrop splash detachment   |   |
| Surface protection-wind | Protects soil surface from detachment and transport of soil particles by sheer forces                                     |   |
| Overland flow reduction | Reduces overland or surface flow of water by creating a maze of 'mini-dams'.  | Longer fiber length provides better protection;<br><br>Blown on mulch results in better soil surface contact  |
| Temperature protection  | Mulch reduces solar input to the soil by reflecting solar energy.   | The color of a particular mulch plays an important part in this process. Darker mulch absorbs more heat energy, for instance.   |
| Evaporation protection  | Mulch reduces evaporation by reducing surface temperatures as well as by creating a physical barrier                      |   |
| Nutrient addition       | Organic mulches contain carbon and other organic nutrients that can enhance both organic matter and nutrients in the soil | Nutrient and energy additions are variable and depend upon the material. For instance, straw is known to contain very little C and N while pine needles can be much higher. Wood chips may lock up N but contain high amounts of C. |

In the Tahoe Basin, an ongoing study by Grismer and Hogan (in submission) found that mulches can reduce sediment delivery by an order of magnitude. Edwards and Burney (1987) found that mulch minimized effects of both compaction and freeze thaw on a range of soils (silt, sandy loam, fine sandy loam). Battany and Grismer (2000), showed that in a California vineyard, soil loss was linked to soil cover.

## *Pine needles*

Pine needles have been used in the Lake Tahoe Basin and elsewhere as a surface mulch since 1992. However, little research has been done on pine needle effectiveness. Pannkuk and Robichaud (2003) studied pine and fir needle cast following fires on both volcanic and granitic soils and found that a 50 percent cover of Douglas fir needles reduced interrill erosion by 80 percent and rill erosion by 20 percent. A 50 percent cover of ponderosa pine needles reduced interrill erosion by 60 percent and rill erosion by 40 percent. (Wright, Perry, and Blaser 1978).

Pine and fir needles offer advantages over some short-lived mulches such as straw since they last anywhere from two to ten times as long, thus providing services over longer periods of time. Grismer and Hogan have been assessing pine needle effectiveness for a number of years. Reports currently in press or in submission describe the positive effects of pine needles on plant growth and erosion reduction (Caltrans Demonstration and Development Report, in preparation by Grismer & Hogan). They have shown that some of the highest infiltration rates, as well as the highest plant cover rates on restoration sites, have occurred under a pine needle mulch. Modeled after native forest surface cover, the use of pine needles has shown very promising results.

## TILLING TREATMENT ISSUES

Removal of compaction and/or reduction of soil density is a critical component of restoring hydrologic function to soil. Froehlich and McNabb (1984) showed that compaction may last up to 30 years and can reduce stand growth in Pacific Northwest forests by up to 15%. Tillage of compacted soil can be effective in reversing compaction. Luce showed that on a highly compacted road that had been ripped, saturated hydraulic conductivity can be up to 35 mm/hr, or approximately half of the natural background. However, Luce (1997) also suggested that this rate represented a significant increase in infiltration and would effectively reduce runoff and thus erosion during rainfall events of over 1" per hour.

Grismer and Hogan measured infiltration rates of fully treated (wood chips tilled into a highly compacted soil) of over 4 inches per hour on a Tahoe area ski run (Hogan 2004b). Torbert and Burger (2000) reporting on research by Larson and Vimmerstedt (1983), stated that compaction is likely the most important mine reclamation problem in need of solution. They stated that compaction is caused during several steps of reclamation construction such that soil bulk density is reduced to root limiting levels.

## ECONOMIC CONSIDERATIONS IN TREATMENTS

An extremely important consideration in designing and implementing a restoration, erosion control or revegetation project is the cost. One approach that needs further study is the 'cost over time' or 'cost per unit time' aspect.

The cost of implementing an erosion control project is often measured as the cost of applying material to the project area. However, if we regard the replacement of function to that site as a primary goal and add the element of time, the question becomes: "How well does this project function and for how long?" For instance, if straw mulch is used and lasts two seasons and costs \$1000/ac compared to pine needle mulch which may cost \$2500/acre but lasts five seasons, then the actual cost would be exactly the same per year effectiveness. More cost effectiveness assessments will be critical to determining the actual costs of projects, not just the application cost. Many projects in the Lake Tahoe Basin have been re-treated using the same, relatively inexpensive techniques (hydroseeding, no soil preparation) two and three times and still have not performed adequately (personal communication, Jason Drew- NRCDC, Joe Pepi-California Tahoe Conservancy; Larry Benoit-Tahoe Regional Planning Agency). At that point, the question becomes: "How many times do you apply something that doesn't work before realizing that resources are not being spent effectively?"

## CONCLUSION

Disturbance and erosion need to be considered in a holistic, systemic and functional context in order to develop effective strategies to reduce or control that erosion (Dudley and Stolton 2003). If the 'system' within which erosion takes place is ignored, erosion control measures are unlikely to succeed over the long term. It would be useful to present information and techniques that would clearly show how to successfully stop erosion. However, the paucity of information has led to the creation of the CAREC plot sites.

While a great deal of information has been published about the control of erosion, little of that information provides a complete picture of what is required at each site. Further, most erosion-related research tends to be single variable manipulation studies such as mulch, seed, fertilizer, plant type and so on (see "State of Erosion Control Knowledge" above). Beyond the single variable consideration, most studies are also point in time studies, which means they don't tend to measure results over a multi-year period. This type of information can be incomplete at best and misleading at worst. Field practitioners must deal with multiple variables and do so over several seasons.

Based on this Literature Review the following information gaps have been identified as key areas for additional inquiry, research and documentation in alpine areas:

- The need for better quantification of treatments vs. modeling or guesswork
- Mulches
- BMP effectiveness, especially biological and soil-based BMPs
- Runoff simulation
- Seeding rates
- Tilling depths
- Soil shear and tensile strength measurements
- Compaction and runoff correlation
- Large scale soil loosening effectiveness and efficiency
- Freeze thaw protection with mulch and organic matter
- Improved calibration of the runoff ("C") coefficient for watershed hydrology models

This situation presents us with both restrictions and opportunities. We are restricted by a lack of complete knowledge on effective erosion control treatments in disturbed alpine areas. However, we are offered the opportunity to gain missing knowledge on our own projects through the use of an adaptive management approach (see Guiding Principles). CAREC is committed to improving our understanding of effective sediment source control treatments in ski resorts, and enhancing all three sections of this Sediment Source Control Handbook. By working together and building on our field trials and knowledge base we can have a meaningful impact on erosion control and watershed health throughout the Sierra Nevada.

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